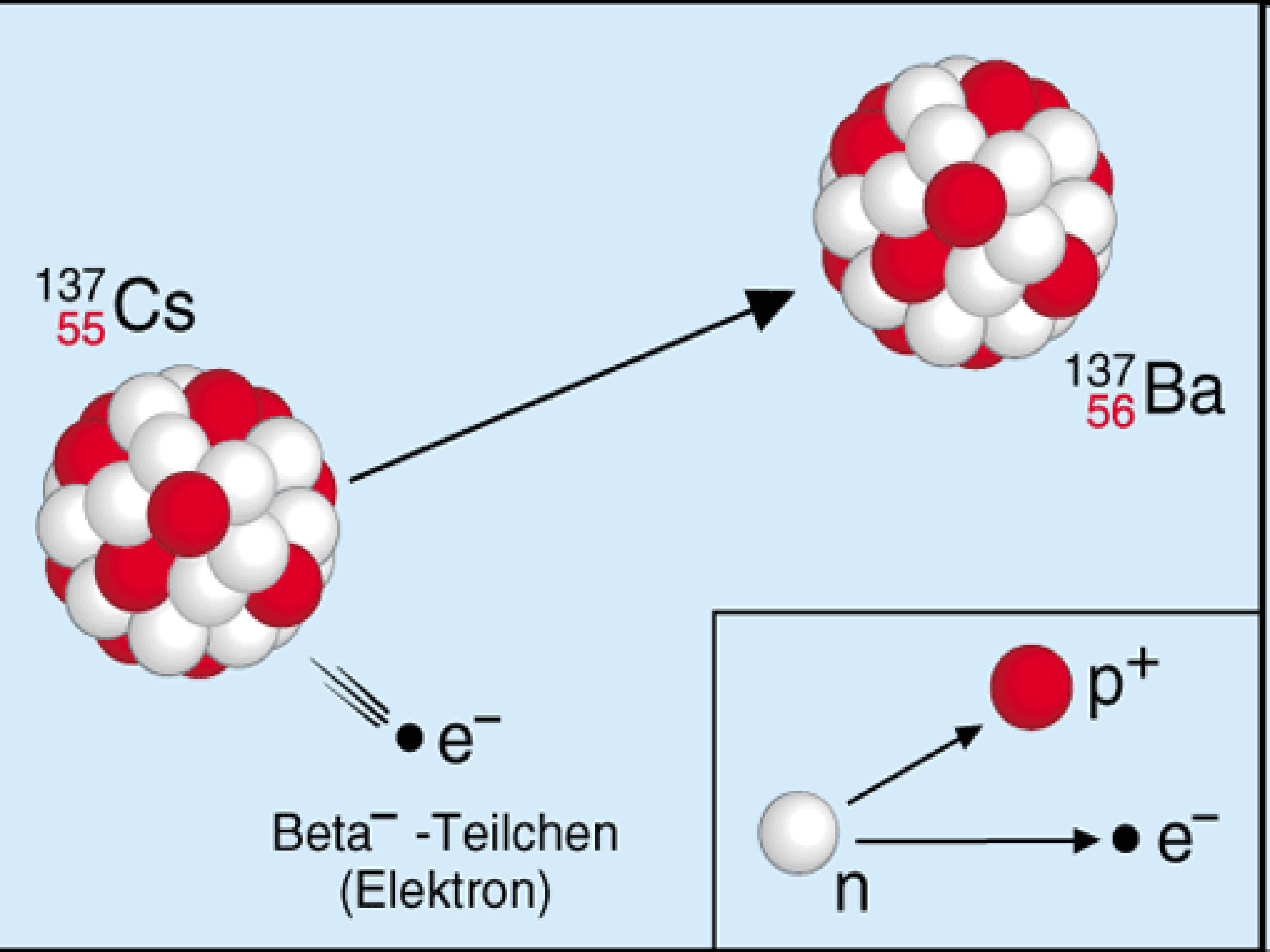
weak

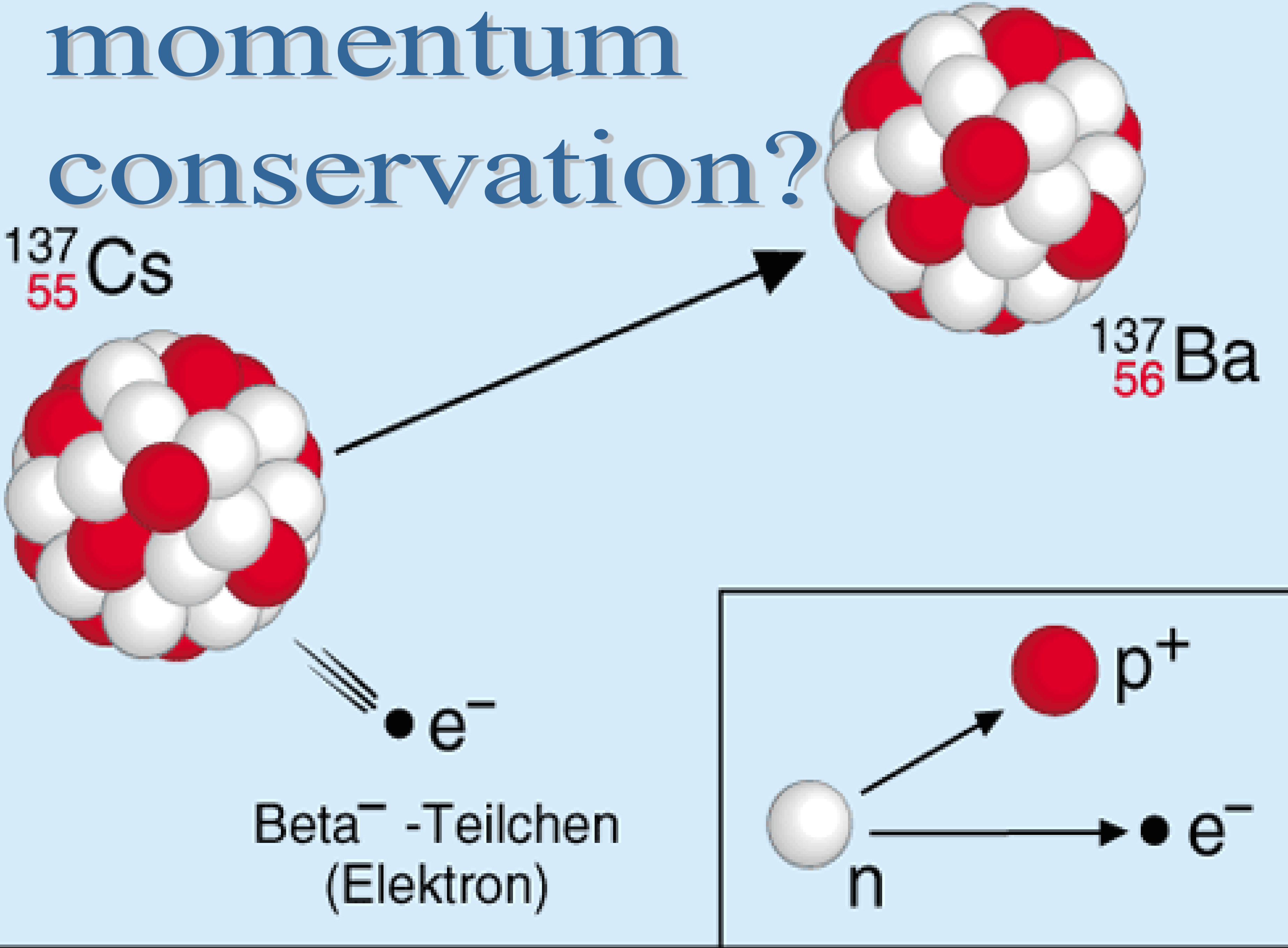
interactions

weak decays

neutron beta decay


$^{137}_{55}Cs$
$^{137}_{56}Ba$
e^-
Beta⁻ -Teilchen
(Elektron)
p^+
n
e^-

momentum conservation?



W. Pauli

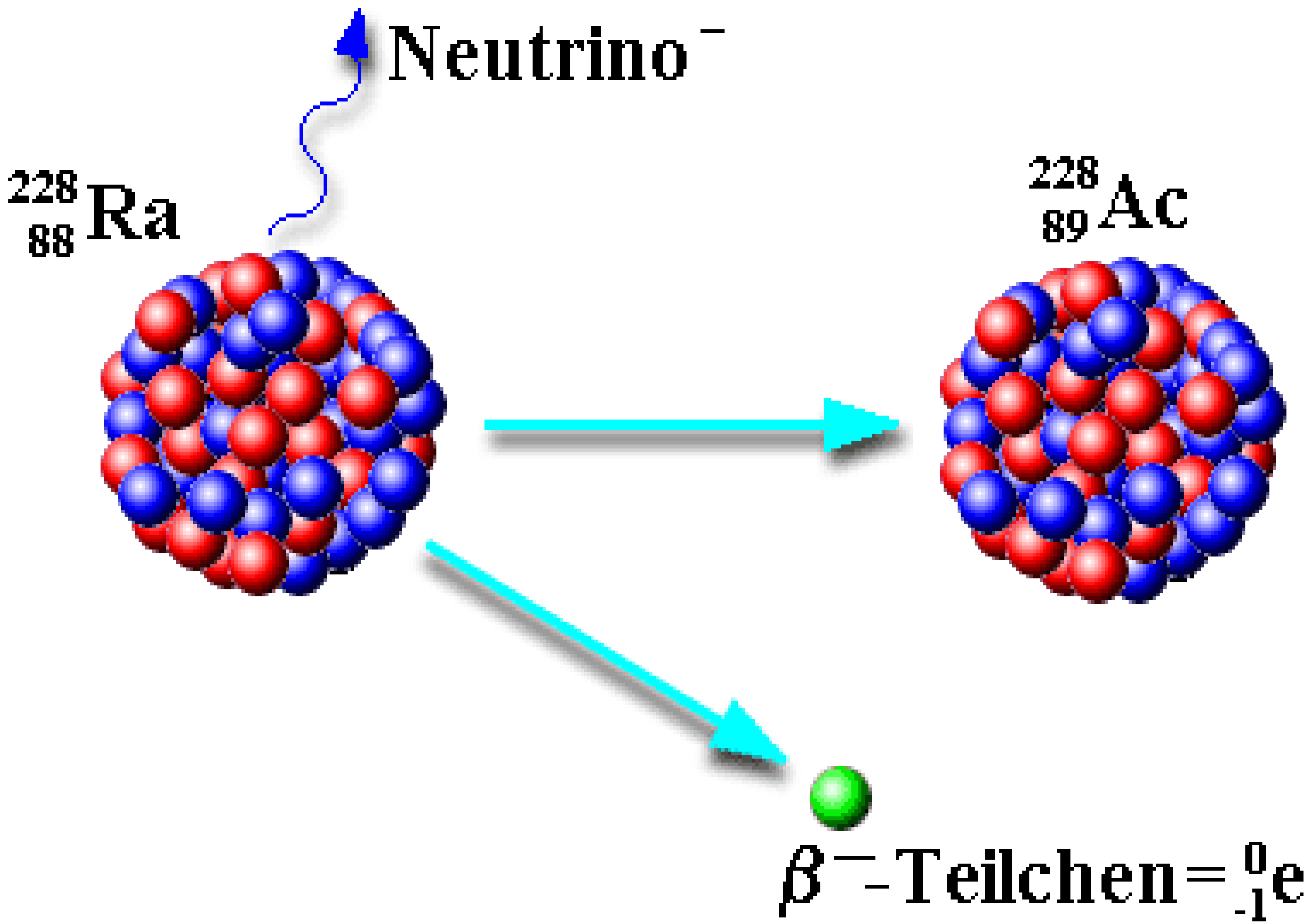
neutrino
1927

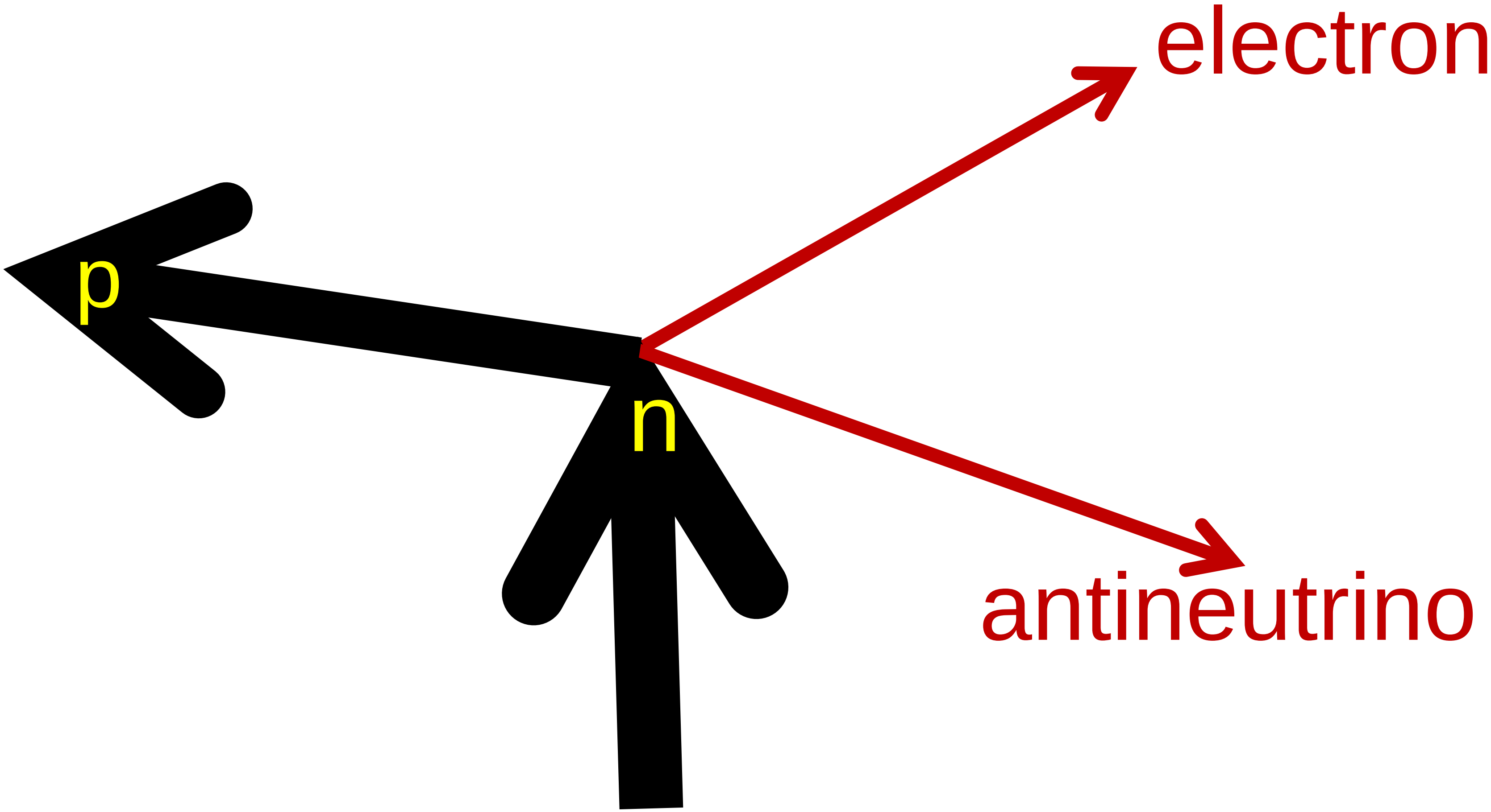
weak decays

beta decay of neutron

$$n \Rightarrow p + e^{-} + \overline{\nu}_e$$

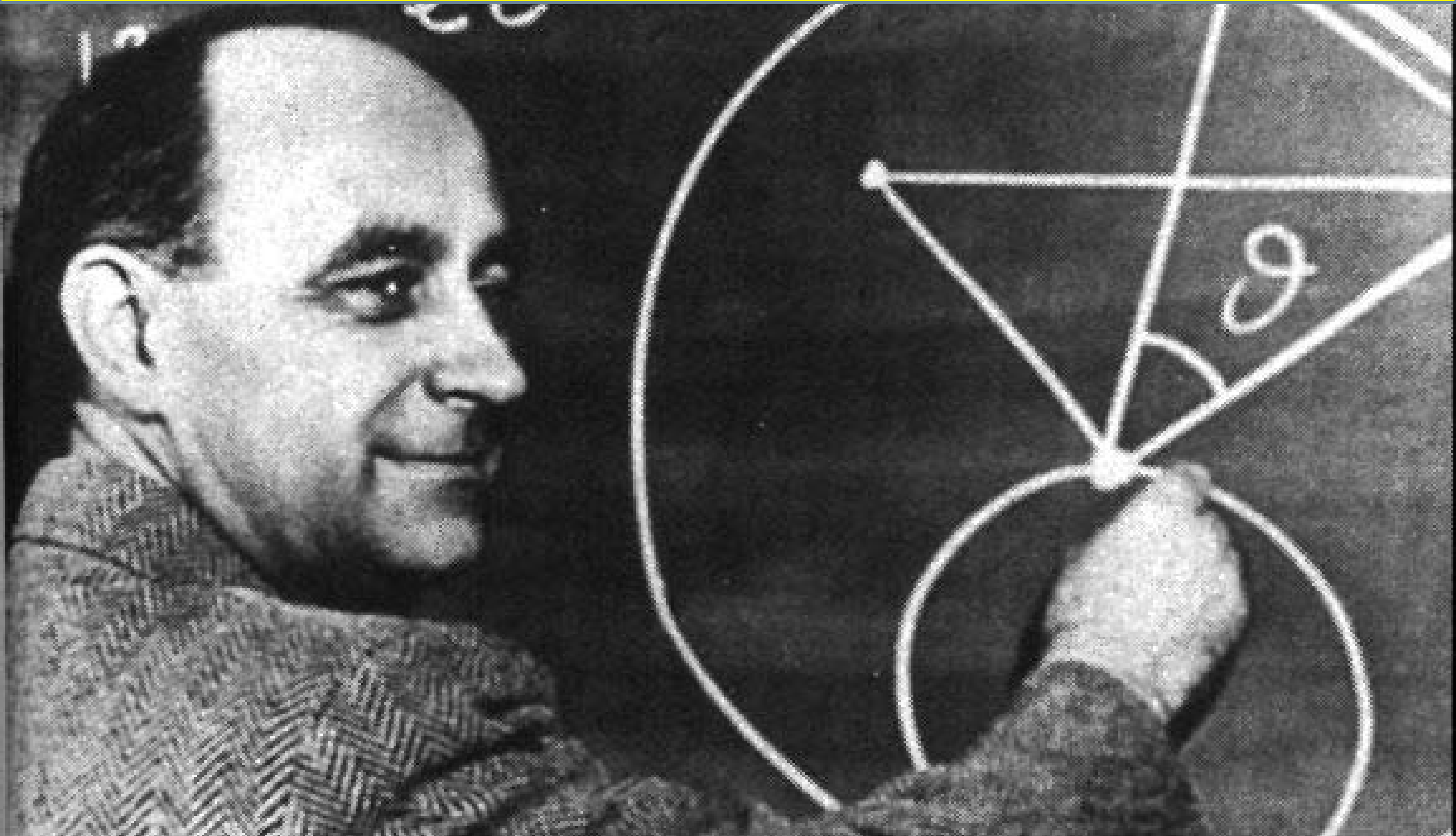
Beta-minus-Zerfall





direct interaction
of four fermions

Fermi interaction



$$\mathcal{L}_{int} = \sim G\, \bar{\psi}_1 \psi_2 \bar{\psi}_3 \psi_4$$

G: Fermi constant

$$G_F = 1.16637 \times 10^{-5}\, GeV^{-2}$$

weak interactions

current-current interaction

weak currents ~ lefthanded:

$$j_\mu(x) = \overline{\psi}(1+\gamma_5)\gamma_\mu\psi$$

$$L_{\text{int}} \propto G_F\, j_\mu\, j^\mu$$

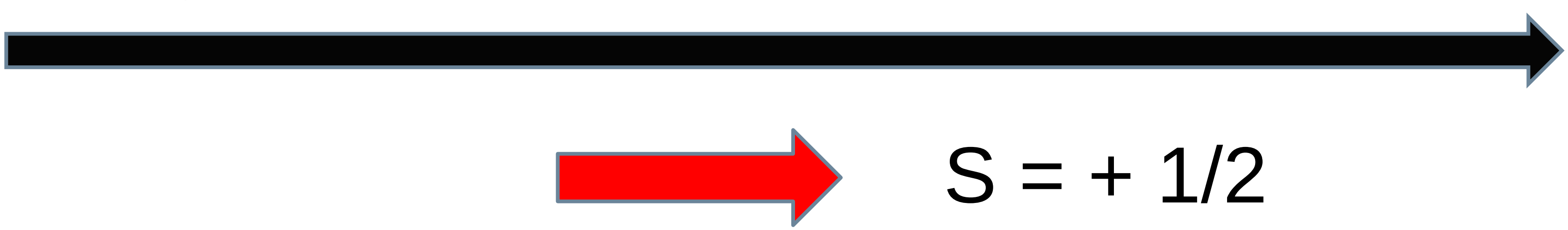
Feynman / Gell-Mann
Marshak / Sudarshan

1958

lefthanded fermion

S= - 1/2

righthanded antifermion



S = + 1/2

maximal breaking

of

parity

weak interaction of the quarks

beta – decay

d → u

$$n \Rightarrow p + e^{-} + \bar{\nu}_e$$

$$weak \quad current:$$

$$\bar{d}\gamma_{\mu}(1+\gamma_5)u + h.c.$$

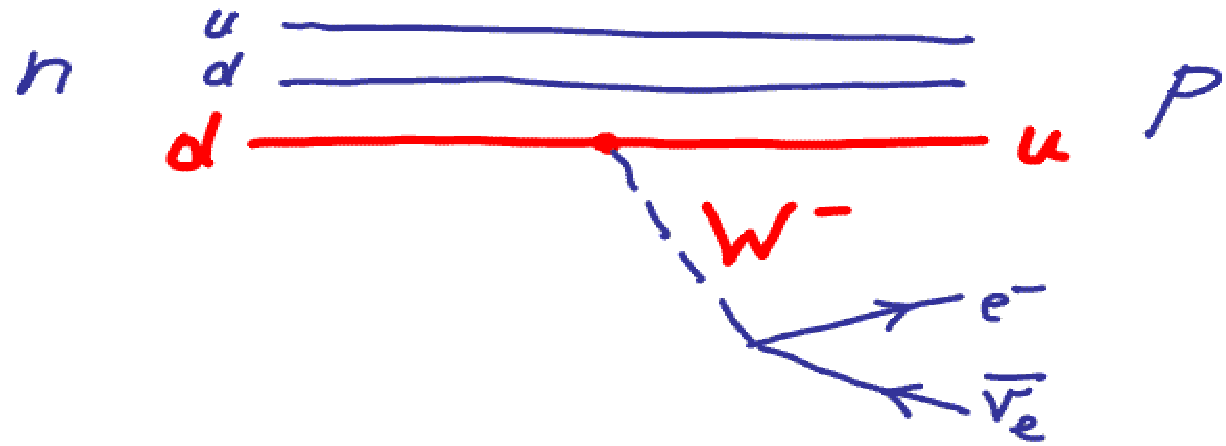
weak decays of strange particles

$$\Lambda \Rightarrow p e^- \bar{\nu}_e$$

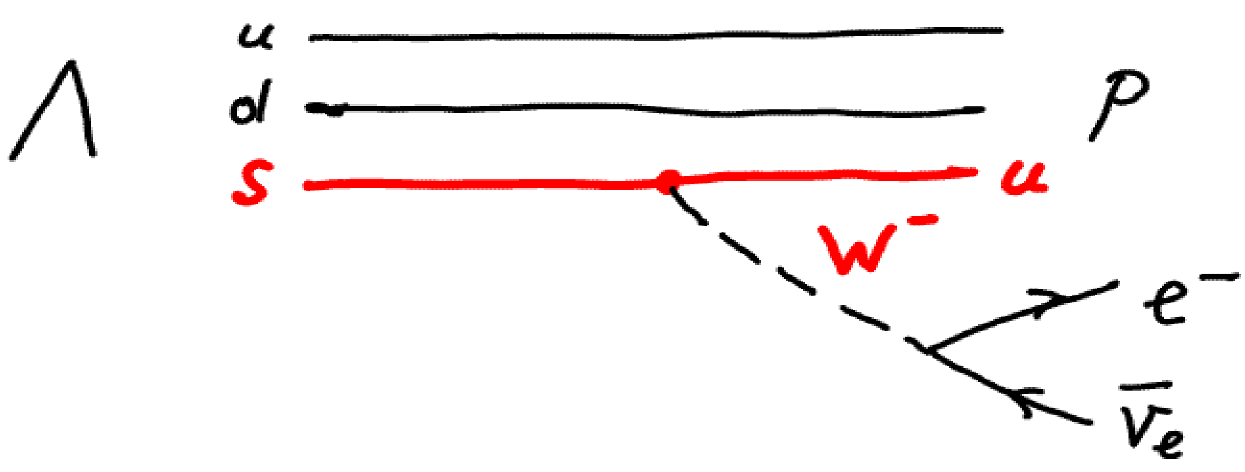
(u d s) (u u d)

s → u

neutron decay:



Λ - decay:



$$\left\langle \frac{u}{d\cos\theta_c + s\sin\theta_c} \right\rangle$$

mixing of mass eigenstates by weak interaction

(Cabibbo angle)

$$\theta_c \approx 13^0$$

N. Cabibbo 1963

(Cabibbo angle)

$\begin{pmatrix} u \\ d \end{pmatrix}$ (s)

W - coupling :

$$u \longleftrightarrow d \cos\theta_c + s \sin\theta_c$$

θ_c : ~ 13,04°

$\cos\theta_c \rightarrow$ 0.974

$\sin\theta_c \rightarrow$ 0.226

$$weak \quad current:$$

$$\left(\bar{d}\cos\theta_c + \bar{s}\sin\theta_c\right)\gamma_\mu\left(1+\gamma_5\right)u + h.c.$$

$$neutral \quad current:$$

$$\bar{d}\gamma_\mu(1+\gamma_5)d$$

$$\bar{s}\gamma_\mu(1+\gamma_5)s$$

$$\bar{d}\gamma_\mu(1+\gamma_5)s + h.c.$$

strangeness changing term not observed in the experiments (decay of K-mesons) !!!

1970

GIM – mechanism

(Glashow, Iliopoulos, Maiani)

$$\begin{pmatrix} u & \vdots & c \\ d' & \vdots & s' \end{pmatrix}$$

c: charmed quark

$$d' = \cos\theta_c \cdot d + \sin\theta_c\, s$$

$$s' = -\sin\theta_c\, d + \cos\theta_c\, s$$

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix}$$

Neutral current:

$$(\bar{u}u + \bar{c}c) - (\bar{d}'d' + \bar{s}'s')$$

$$= \quad \ldots \quad - (\bar{d}d + \bar{s}s)$$

No $\bar{d}s$ / $\bar{s}d$ terms

(cancellation:

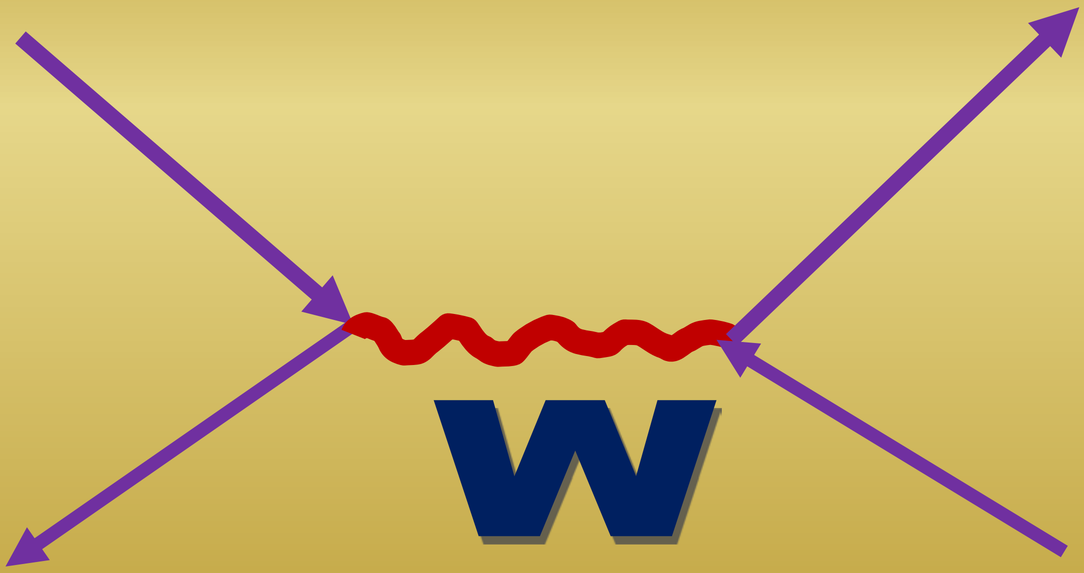
$\bar{d}'d' \sim (\bar{d}s + \bar{s}d)$ term +

$\bar{s}'s' \sim (\bar{d}s + \bar{s}d)$ term −)

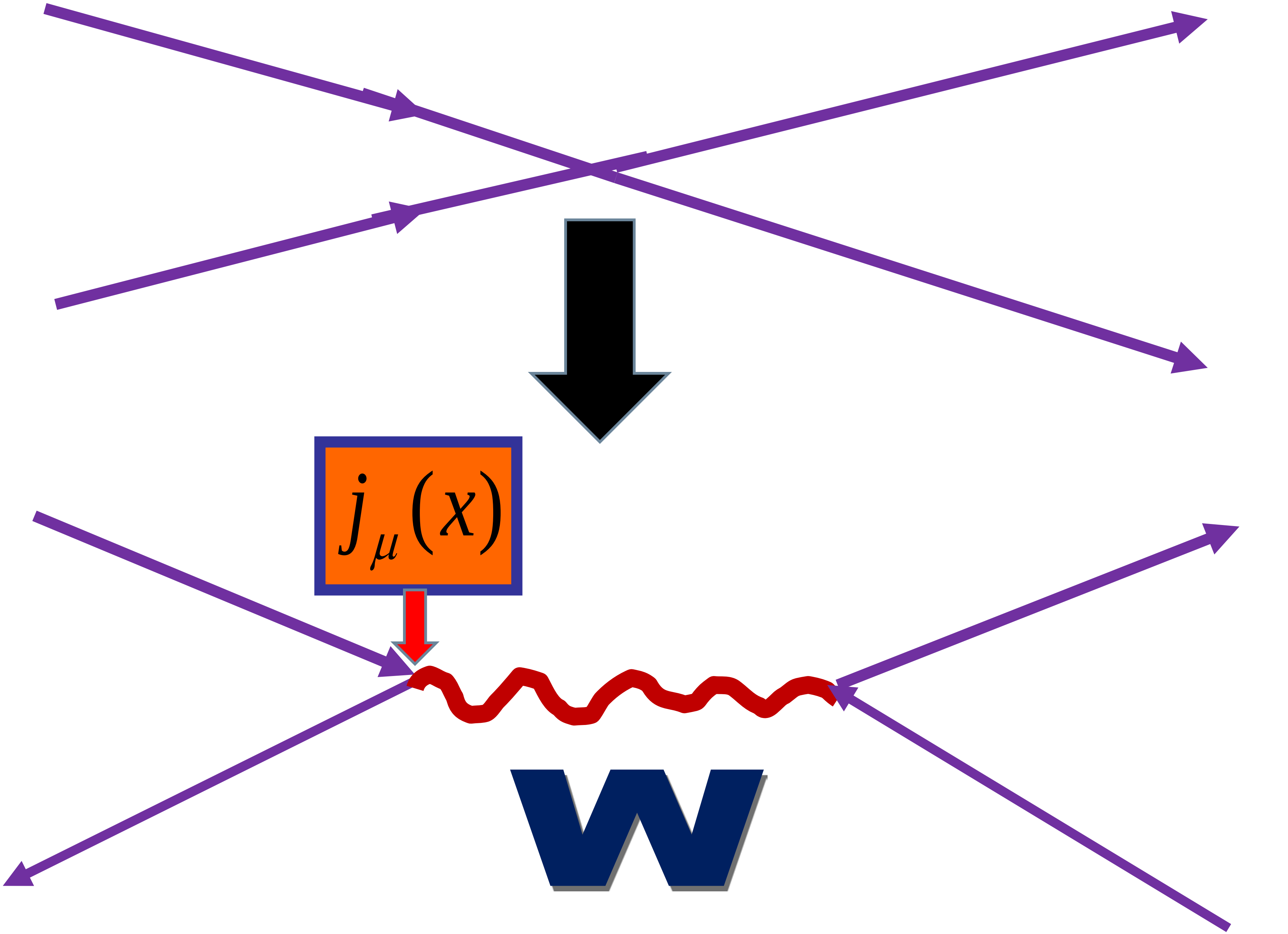
GIM

1957

weak bosons



J. Schwinger



$j_\mu(x)$
W

electromagnetism

+

weak interactions

→ electroweak theory

1964 => 1968
gauge theory of the electroweak interactions

(Glashow, Salam, Weinberg)

U(1)

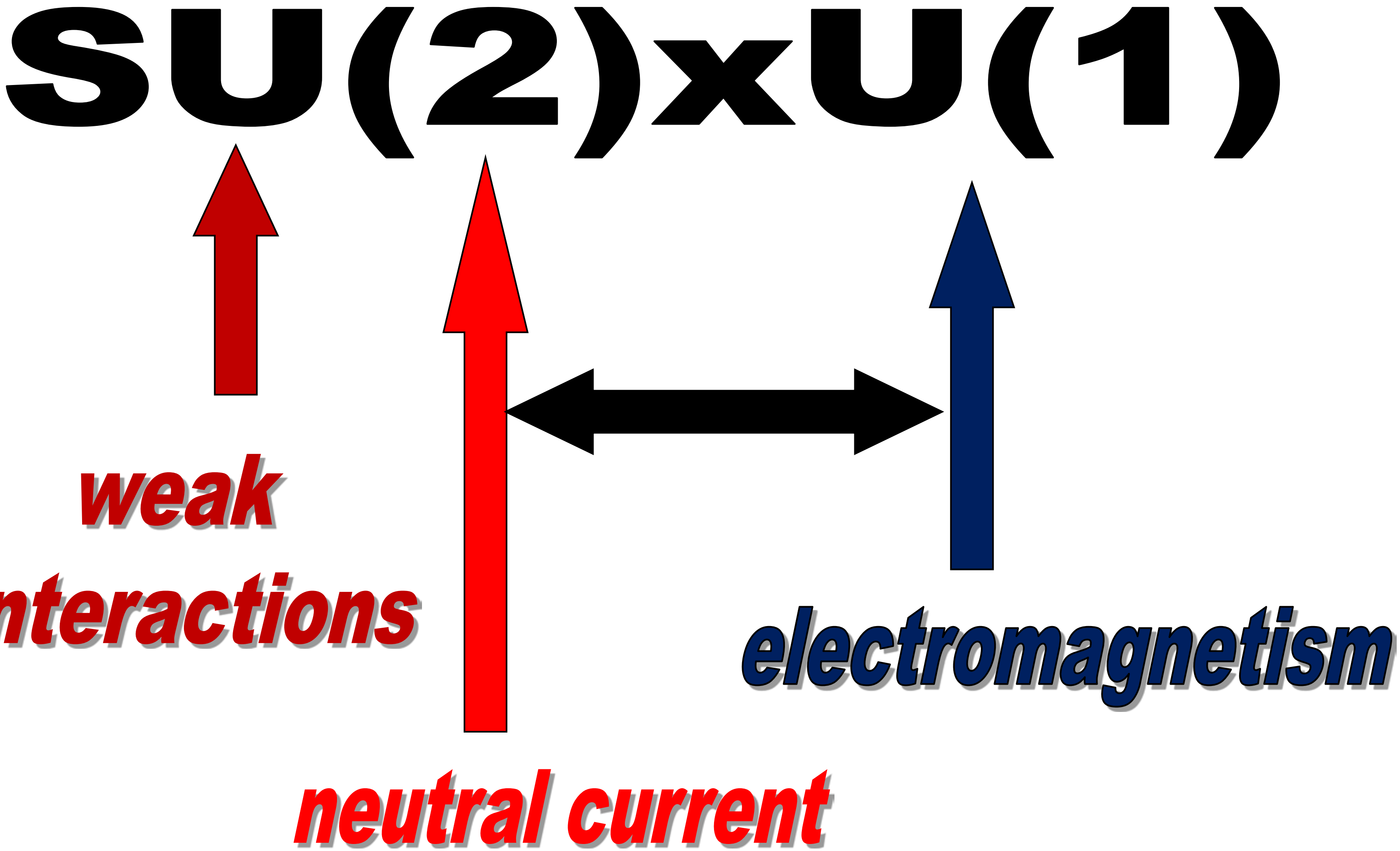
↑

electromagnetism

SU(2)

weak interactions

electroweak theory



1972
Discovery
neutral current
CERN

Electroweak theory of electron and its neutrino

$$Doublet : L \quad = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$$

$$Singlet : R \quad = \left(e^- \right)_R$$

L: lefthanded

R: righthanded

$$Q = T_3 + \frac{1}{2} Y$$

$$Y(e_L^-) = Y(\nu_e) = -1$$

$$Y(e_R^-) = -2$$

Q: electric charge

T: weak isospin

Y: weak hypercharge

SU(2) x U(1)

$$4 \quad gauge \quad bosons:$$

$$W_\mu^i \quad \Rightarrow \quad T_i \quad i = 1,2,3$$

$$B_\mu \quad \Rightarrow \quad Y$$

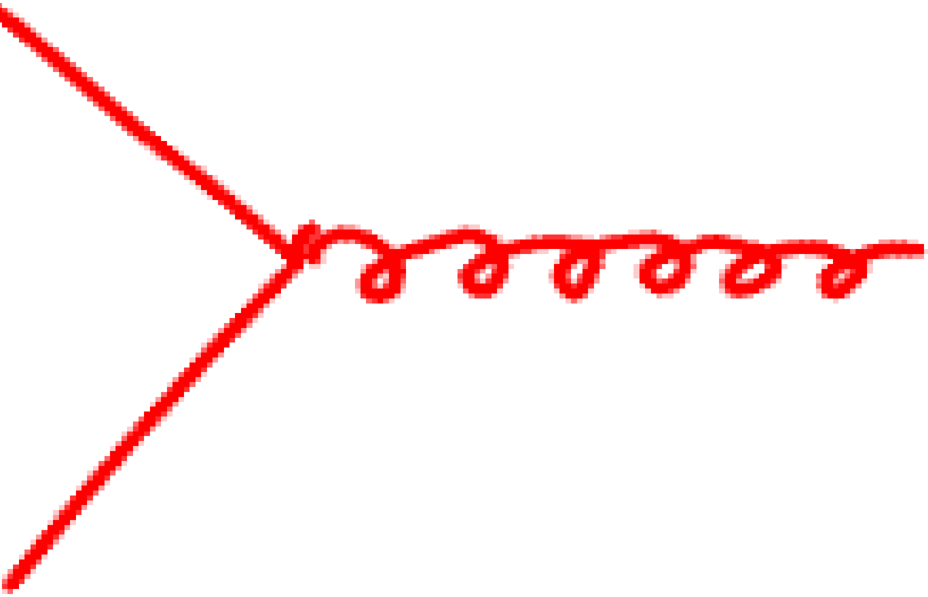
$$L^{g.b.} = -\frac{1}{4} F^{i}_{\mu\nu} F_{i}^{\mu\nu} - \frac{1}{4} G_{\mu\nu} G^{\mu\nu}$$

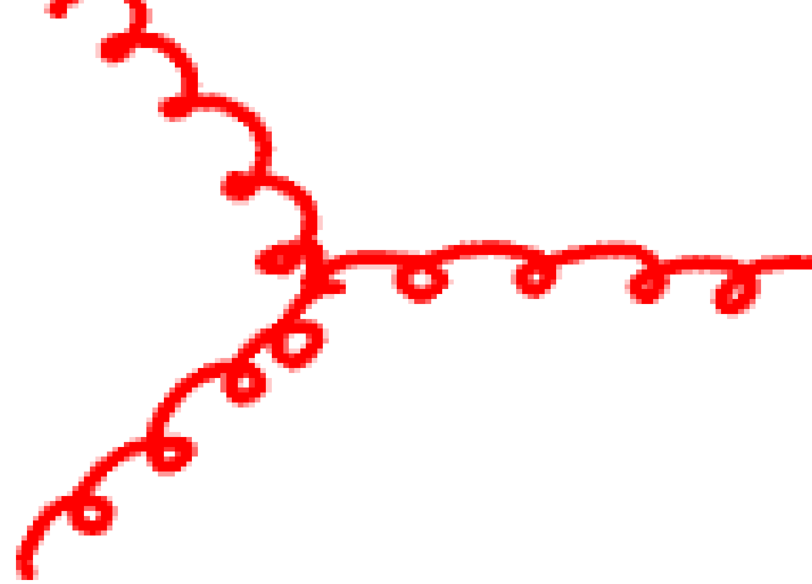
$$F^{i}_{\mu\nu} = \partial_{\nu} A^{i}_{\mu} - \partial_{\mu} A^{i}_{\nu} - g \cdot \varepsilon_{ijk} A^{j}_{\nu} A^{k}_{\mu}$$

$$G_{\mu\nu} = \partial_{\nu} B_{\mu} - \partial_{\mu} B_{\nu}$$

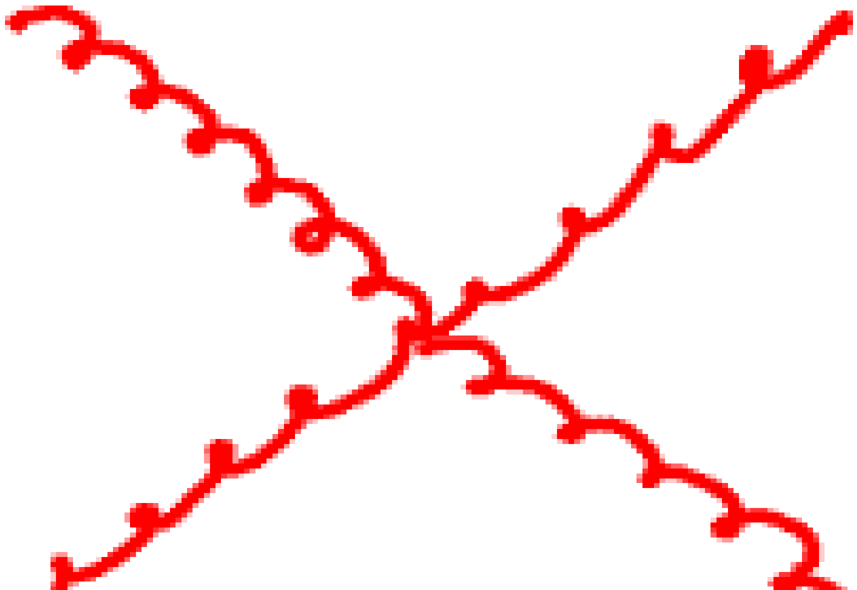
new

quadratic in gauge potential





interactions



Lagrangian of the fermions, interacting with the gauge fields

$$L^f = \bar{L} i \left(\not\partial + i \frac{g}{2} \tau_i \not A_i - i \frac{g'}{2} \not B \right) L + \bar{R} i \left(\not\partial - i g' \not B \right) R$$

„Higgs“ – field doublet of SU(2)

$scalar:$

$$\varphi = \begin{pmatrix} \varphi^{+} \\ \varphi^{0} \end{pmatrix}$$

Lagrangian of the scalars, interacting with the gauge fields

$$L^{scalar} = \left(\partial_\mu \Phi + i\frac{g'}{2}B_\mu \Phi + i\frac{g}{2}\tau^i A_\mu^i \Phi\right)^* \left(\partial_\mu \Phi + i\frac{g'}{2}B_\mu \Phi + i\frac{g}{2}\tau^i A_\mu^i \Phi\right) - V\left(\Phi^*\Phi\right)$$

$$V = \mu^2\left(\Phi^*\Phi\right) + \lambda\left(\Phi^*\Phi\right)^2$$

$$\mu^2 < 0 \Rightarrow \langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}$$

$$v = \sqrt{-\mu^2/\lambda}$$

symmetry breaking:

symmetry breaking:

breaking of SU(2) and U(1)

electric charge conserved

$$M_{W^\pm} = \frac{1}{2} g \cdot v$$

$$Z = \frac{-gA^3 + g'B}{\sqrt{g^2 + g'^2}}$$

photon

$$A = \frac{gB_\mu + g'A^3_\mu}{\sqrt{g^2 + g'^2}}$$

$$M_Z = \frac{1}{2} v \sqrt{g^2 + g'^2}$$

$$M_A = 0$$

$$|\gamma\rangle = \cos\theta_{\mathrm{W}}|B^0\rangle + \sin\theta_{\mathrm{W}}|W^0\rangle$$

$$|Z^0\rangle = -\sin\theta_{\mathrm{W}}|B^0\rangle + \cos\theta_{\mathrm{W}}|W^0\rangle$$

weak angle θ_w:

$$\tan\theta_w = \frac{g'}{g}$$

$$g \cdot \sin\theta_w = g' \cdot \cos\theta_w = e$$

$$\frac{M_W}{M_Z} = \cos\theta_W$$

$G \quad Fermi \quad const.$

$$G \cong 1.166 \bullet 10^{-5} \quad GeV^{-2}$$

$$G/\sqrt{2} = \frac{g^2}{8M_W^2} = 1/2v^2$$

$$\Rightarrow v \cong 246 \quad GeV$$

v vacuum expectation value

of

scalar field

$V \sim 246$ GeV

Neutral current:

$$j_\mu^n = j_\mu^3 - \sin^2\theta_W \, j_\mu^e$$

Z-interaction:

$$\frac{g}{\cos\theta_W} Z^\mu j_\mu^n$$

$$M_W = \frac{37.3}{\sin\theta_W} \text{ GeV}$$

$$M_Z = \frac{74.6}{\sin 2\theta_W} \text{ GeV}$$

Experiment:

$$\sin^2\theta_W (M_Z) =$$

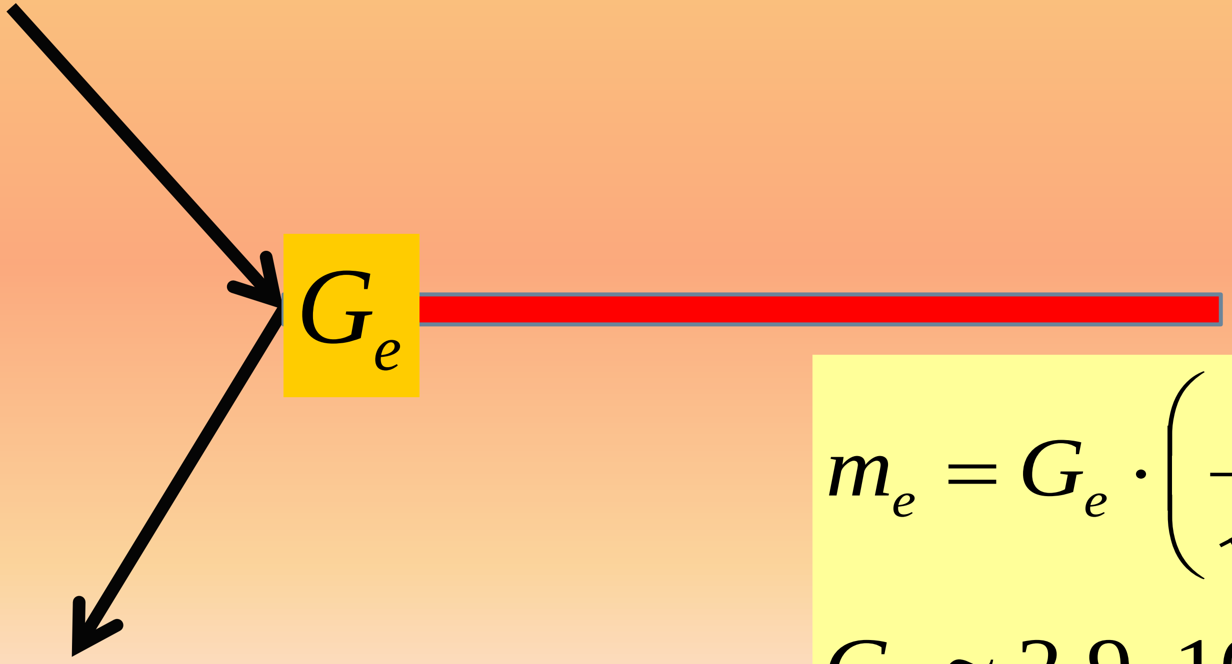
$$0.23120 \pm 0.00015$$

$$M_W = \frac{37.3}{\sin\theta_W} \text{ GeV}$$

$$M_Z = \frac{74.6}{\sin 2\theta_W} \text{ GeV}$$

M(W) ~ 79 GeV
M(Z) ~ 89 GeV

electron mass generated by Yukawa interaction of scalar with fermion



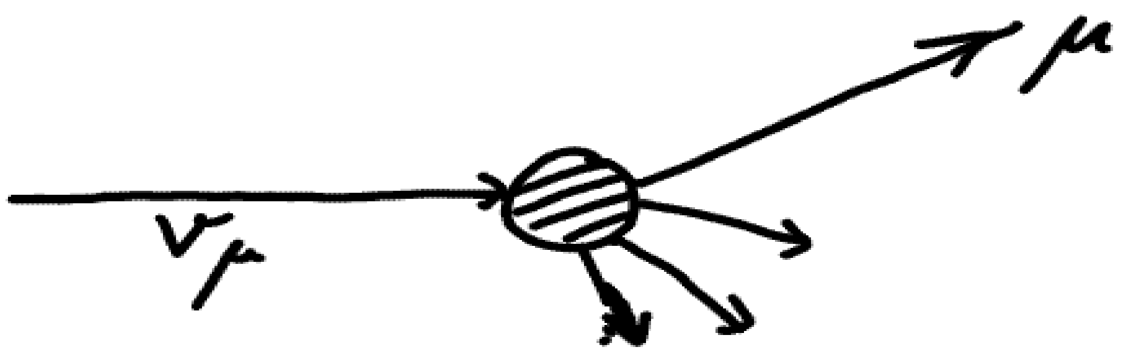
$$m_e = G_e \cdot \left(\frac{v}{\sqrt{2}} \right)$$

$$G_e \approx 2.9 \cdot 10^{-6}$$

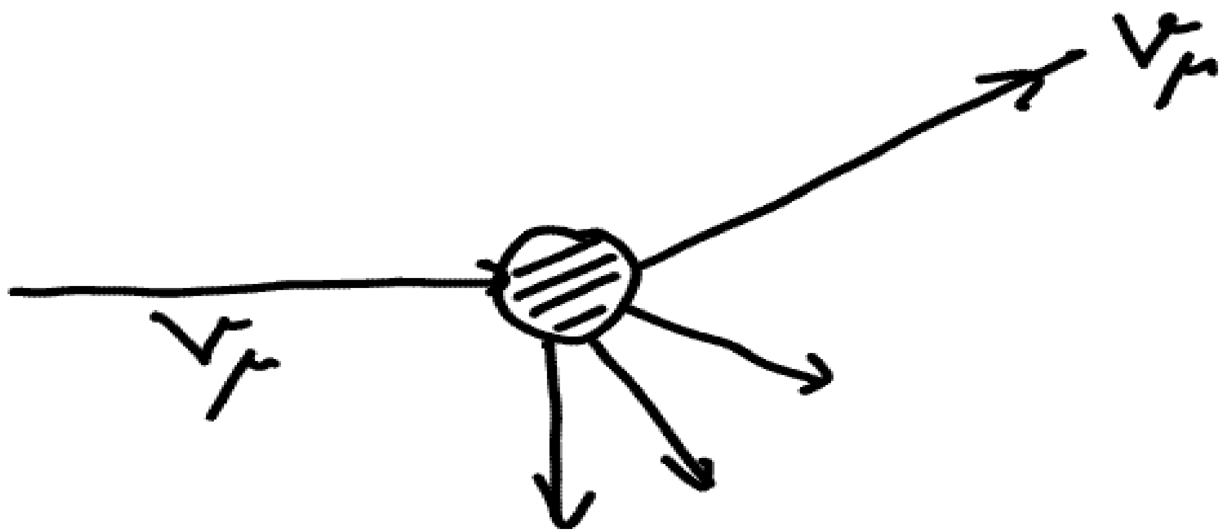
mass matrix of gauge bosons

$$
\begin{pmatrix} A^1 & A^2 & A^3 & B \end{pmatrix}
\begin{bmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & -g'g \\ 0 & 0 & -g'g & g'^2 \end{bmatrix}
\begin{pmatrix} A^1 \\ A^2 \\ A^3 \\ B \end{pmatrix}
$$

Charged current:



Neutral current:



Neutral current:

$$j_\mu^n = j_\mu^3 - \sin^2\theta_w \, j_\mu^e$$

first term

lefthanded

➔ parity violation

experiment at

SLAC (1979)

neutral current

interaction

violates parity !!!

neutral current interaction

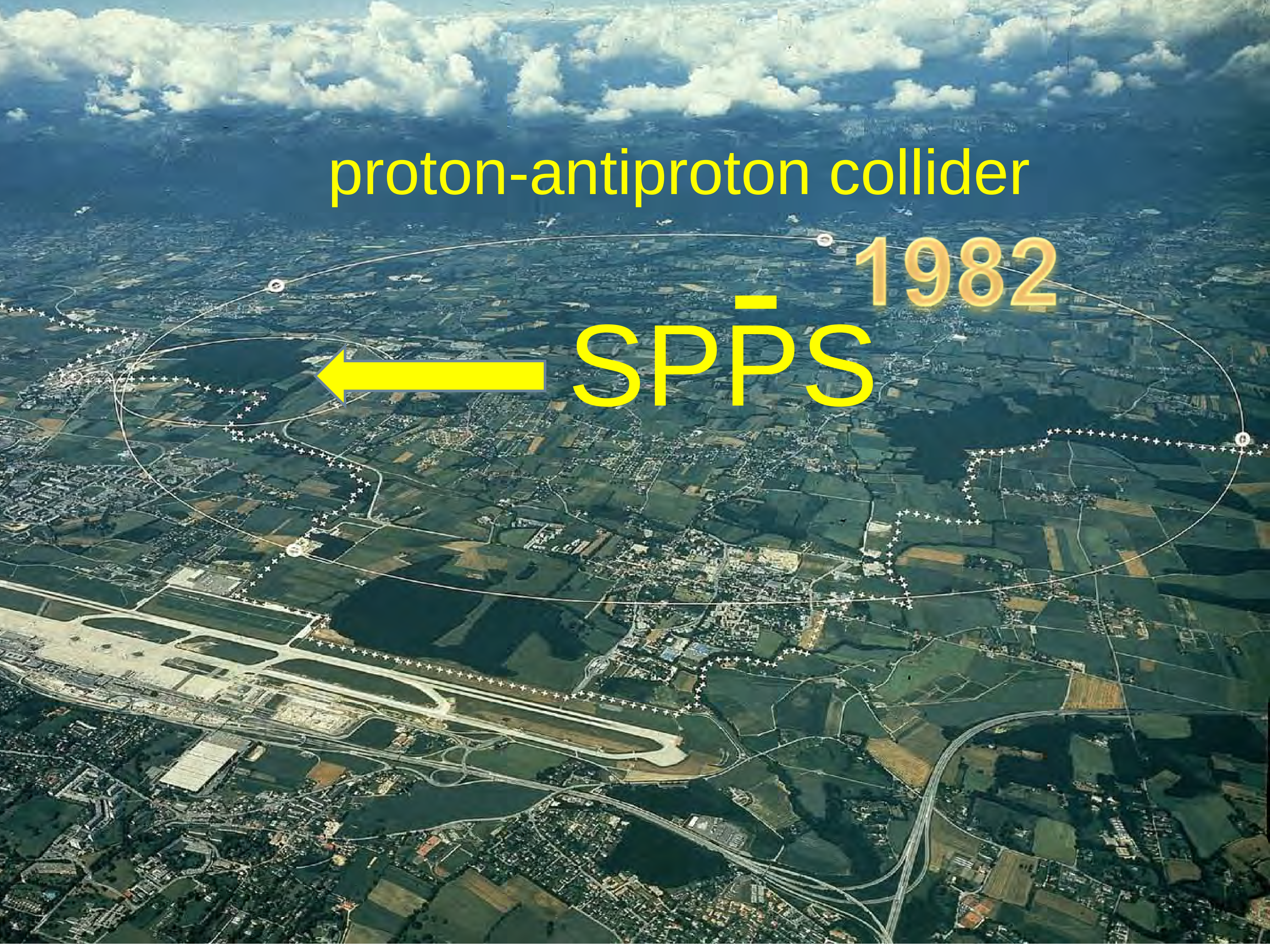
parity violation

observed in atomic physics

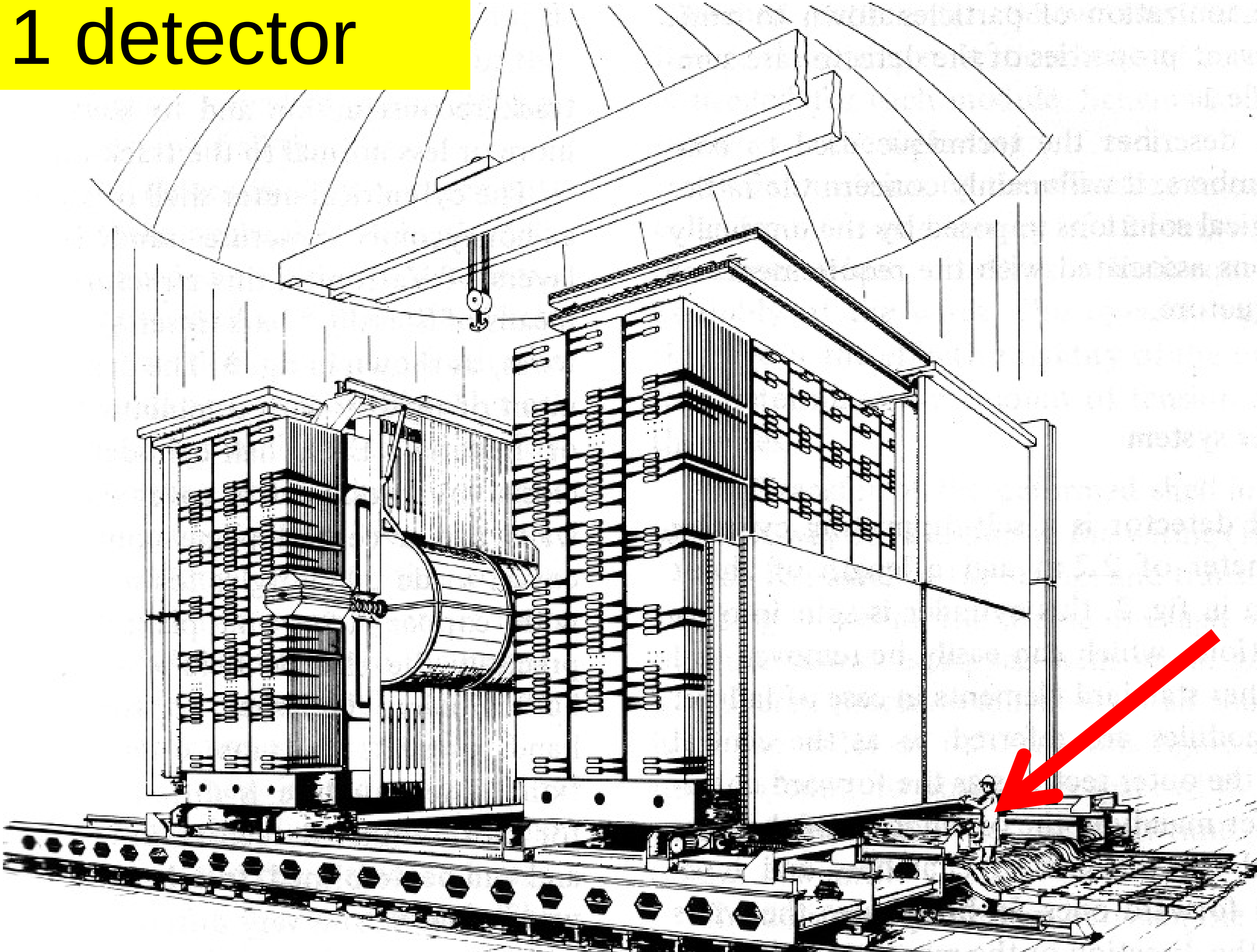

CERN

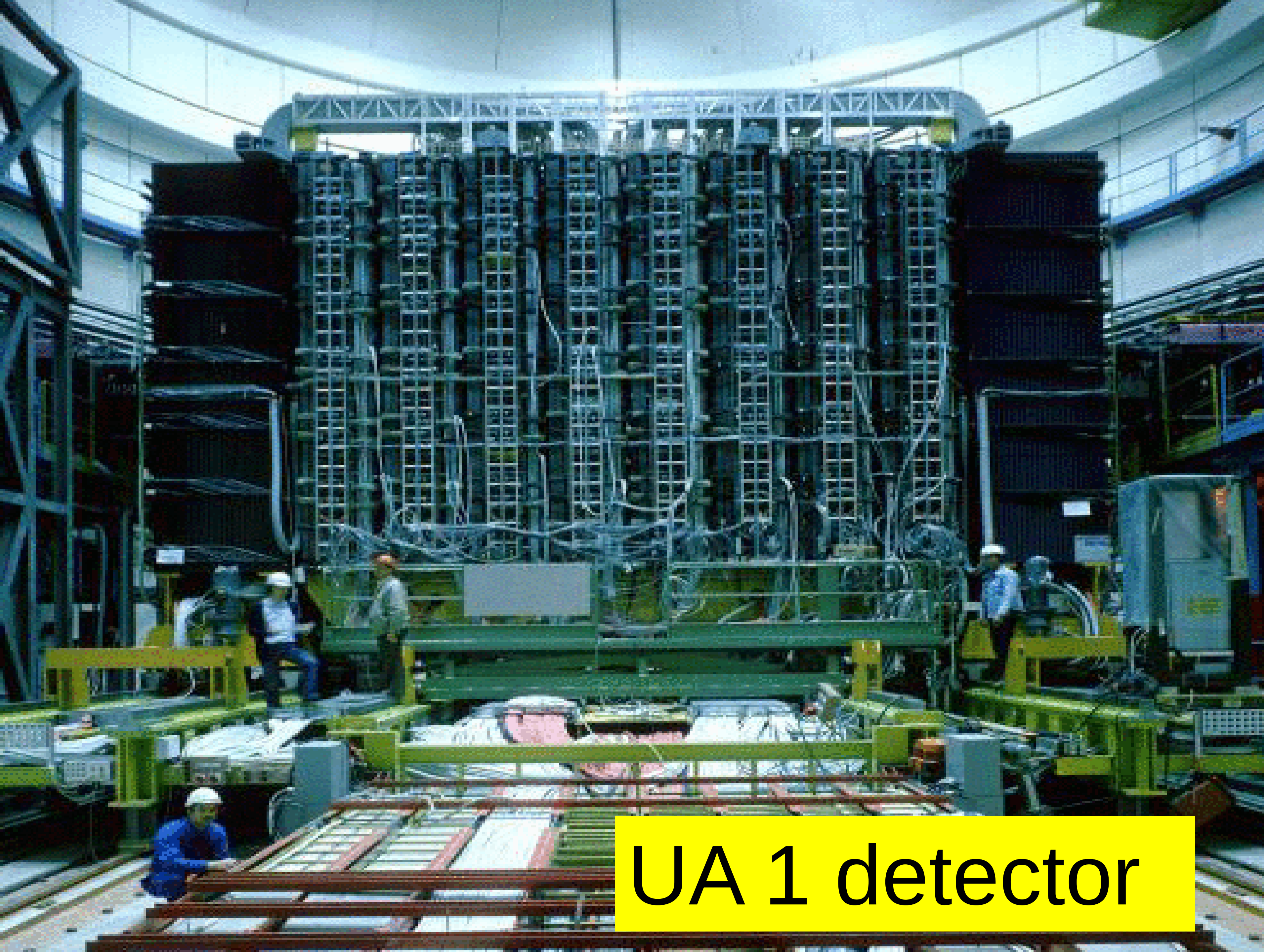

CERN
SPS


SPS

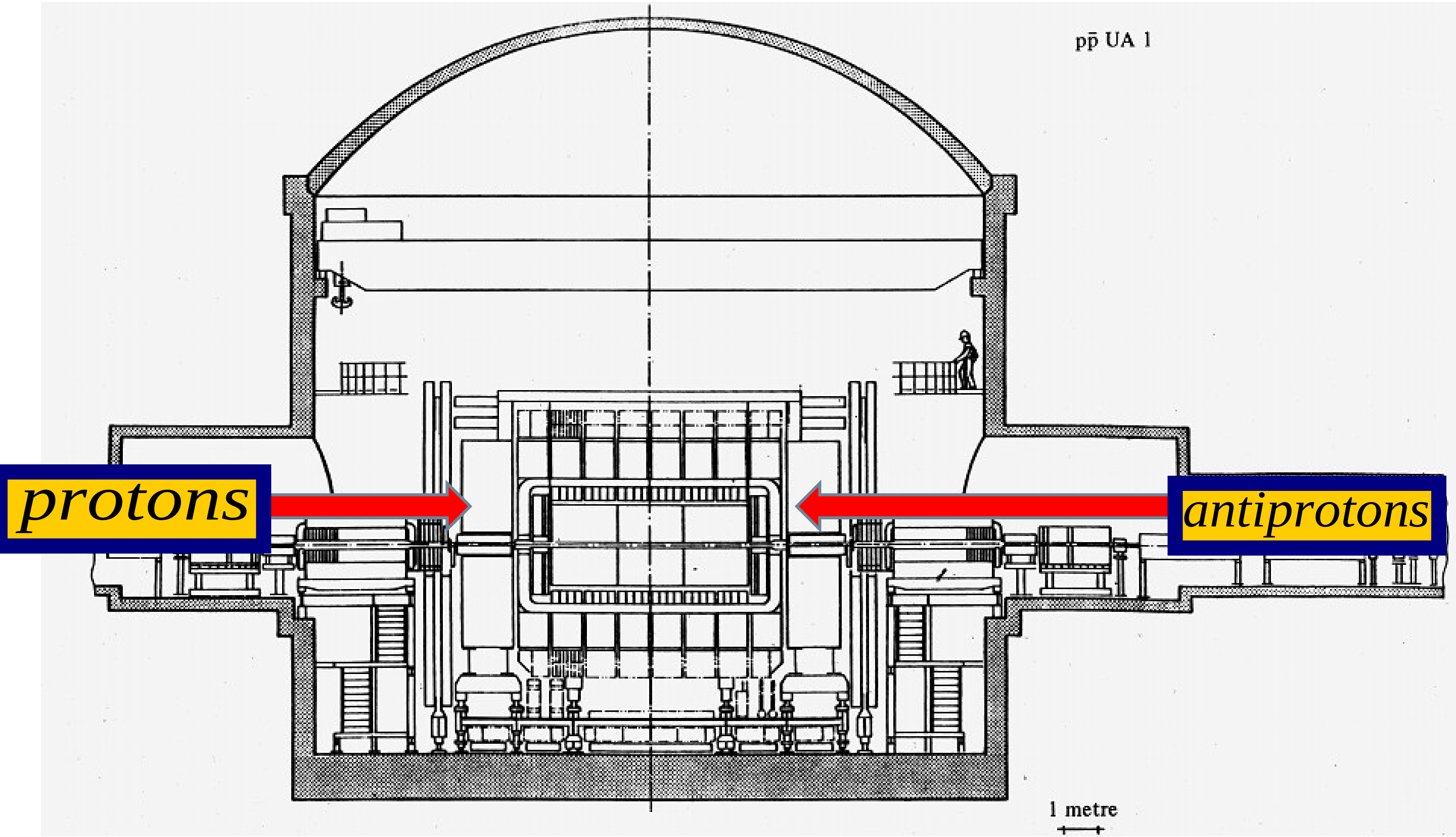

proton-antiproton collider
1982
SPP̄S

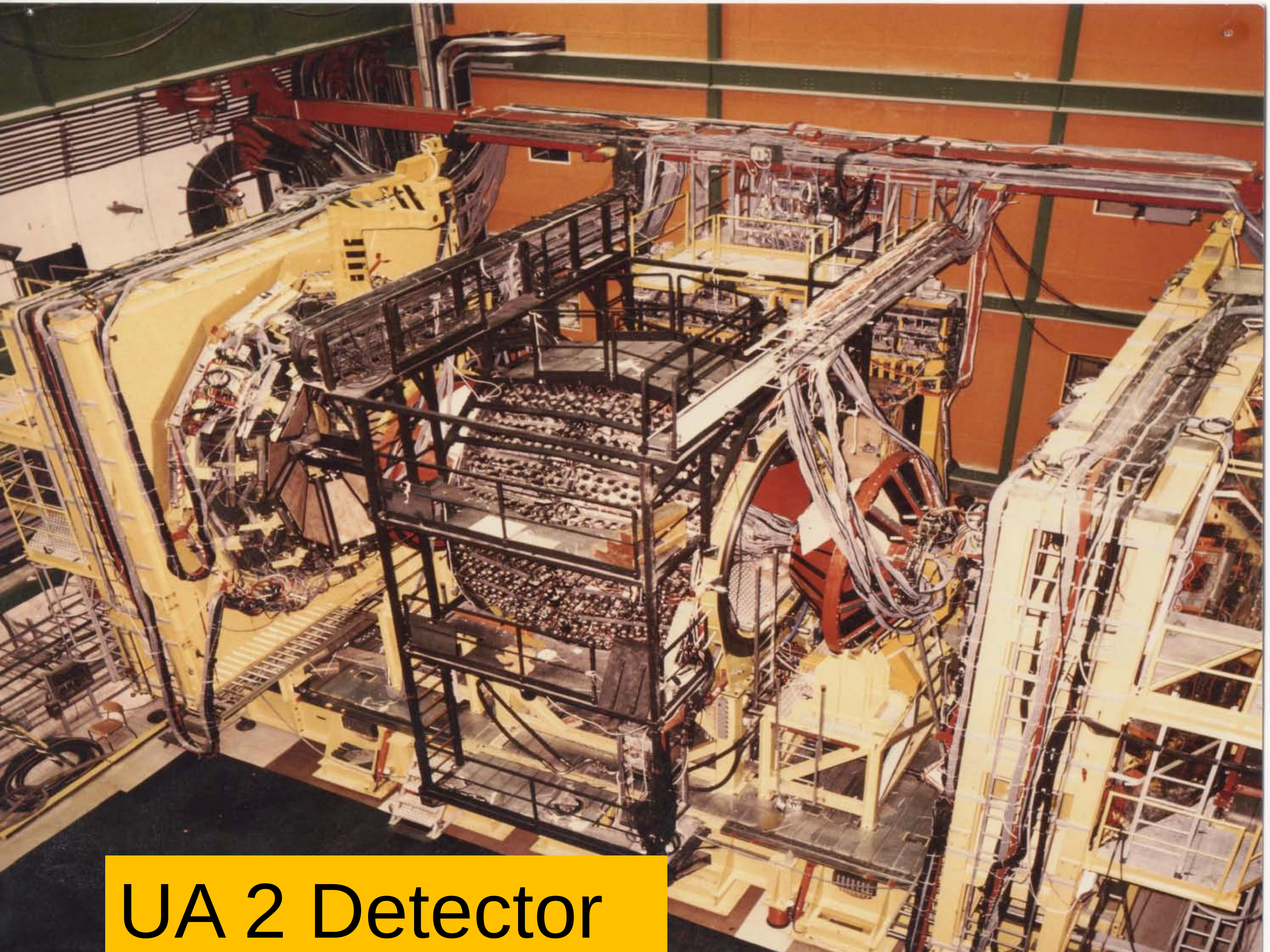
UA 1 detector




UA 1 detector

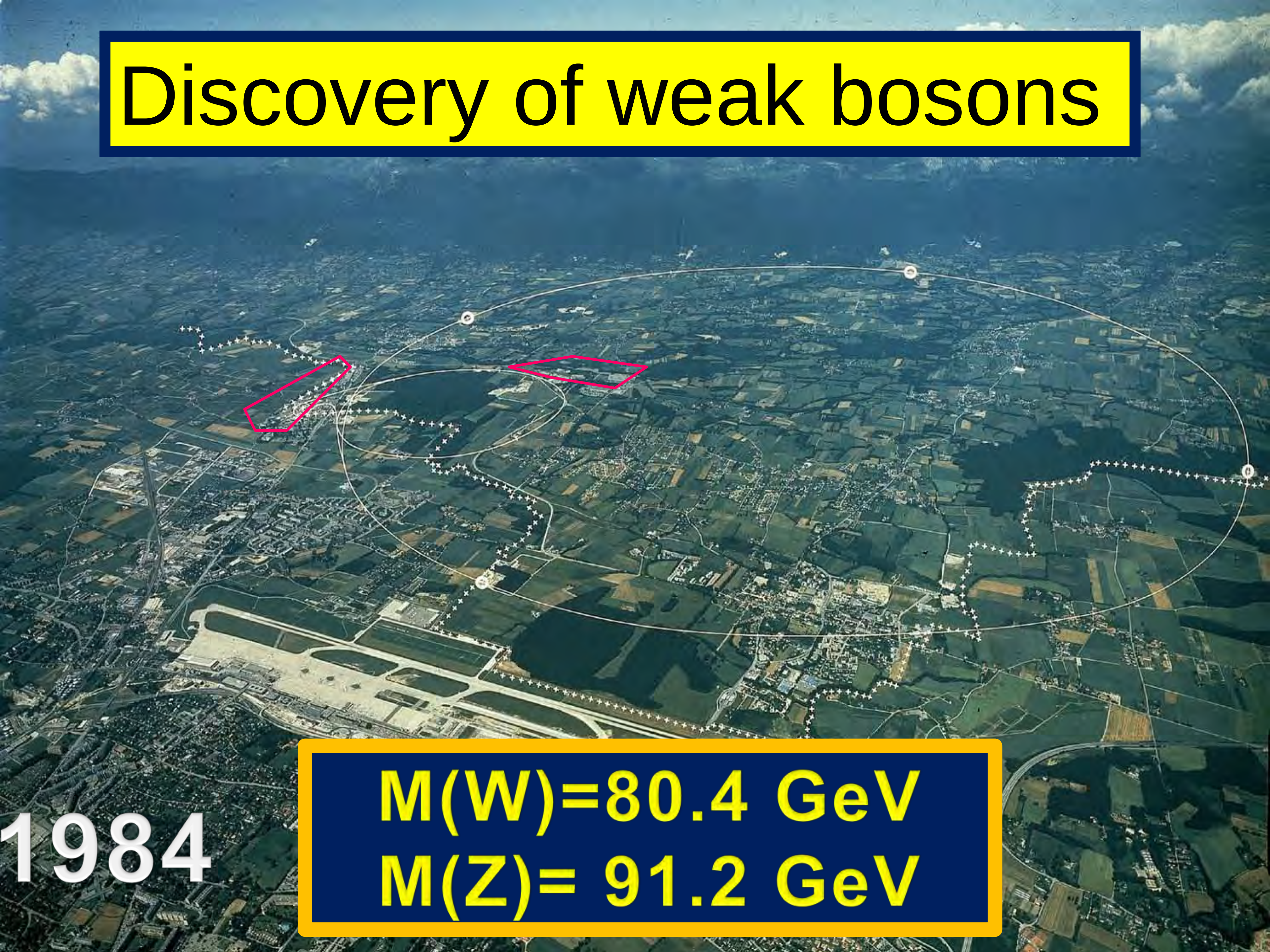
U A 1 detector





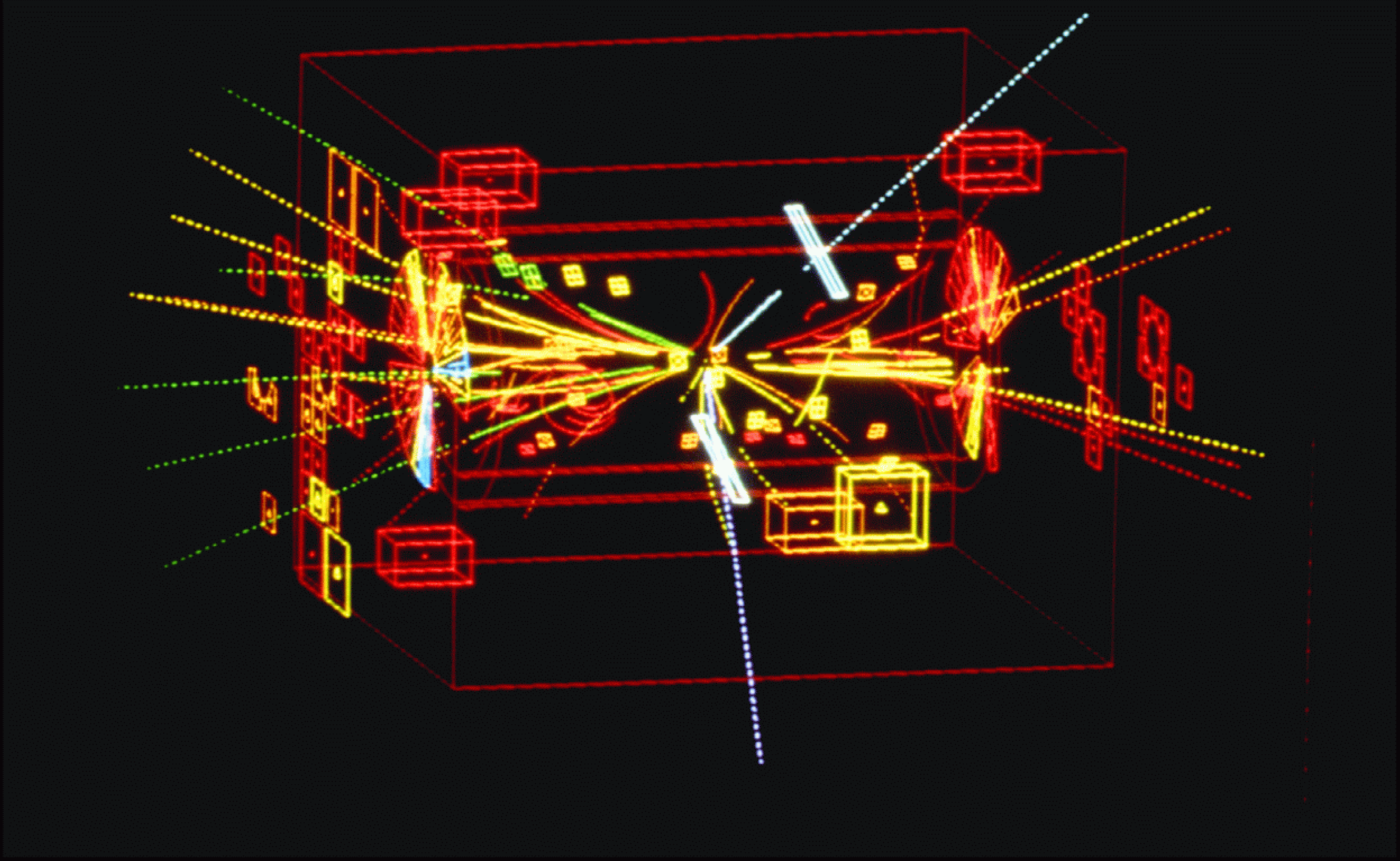
UA 2 Detector

Discovery of weak bosons



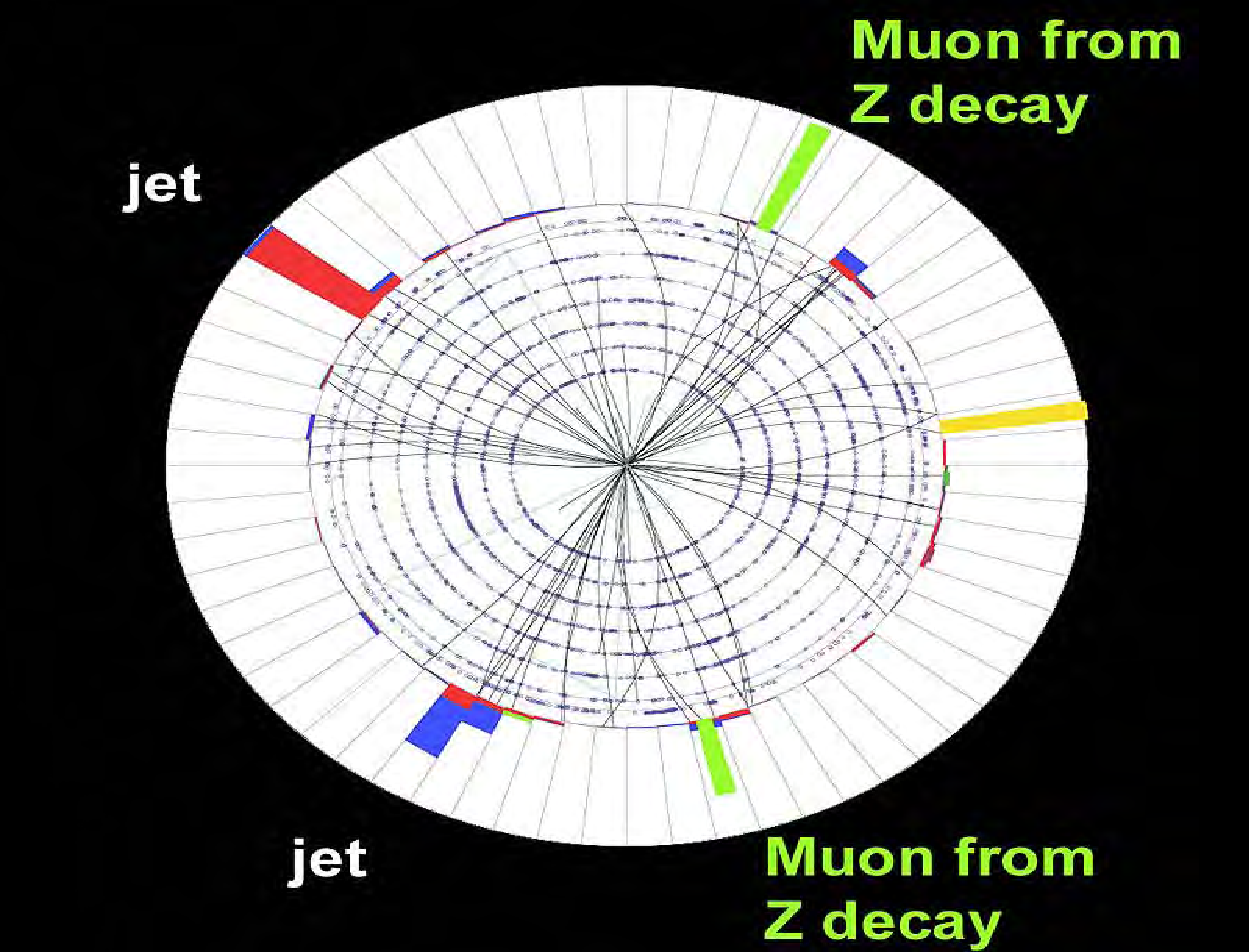
1984

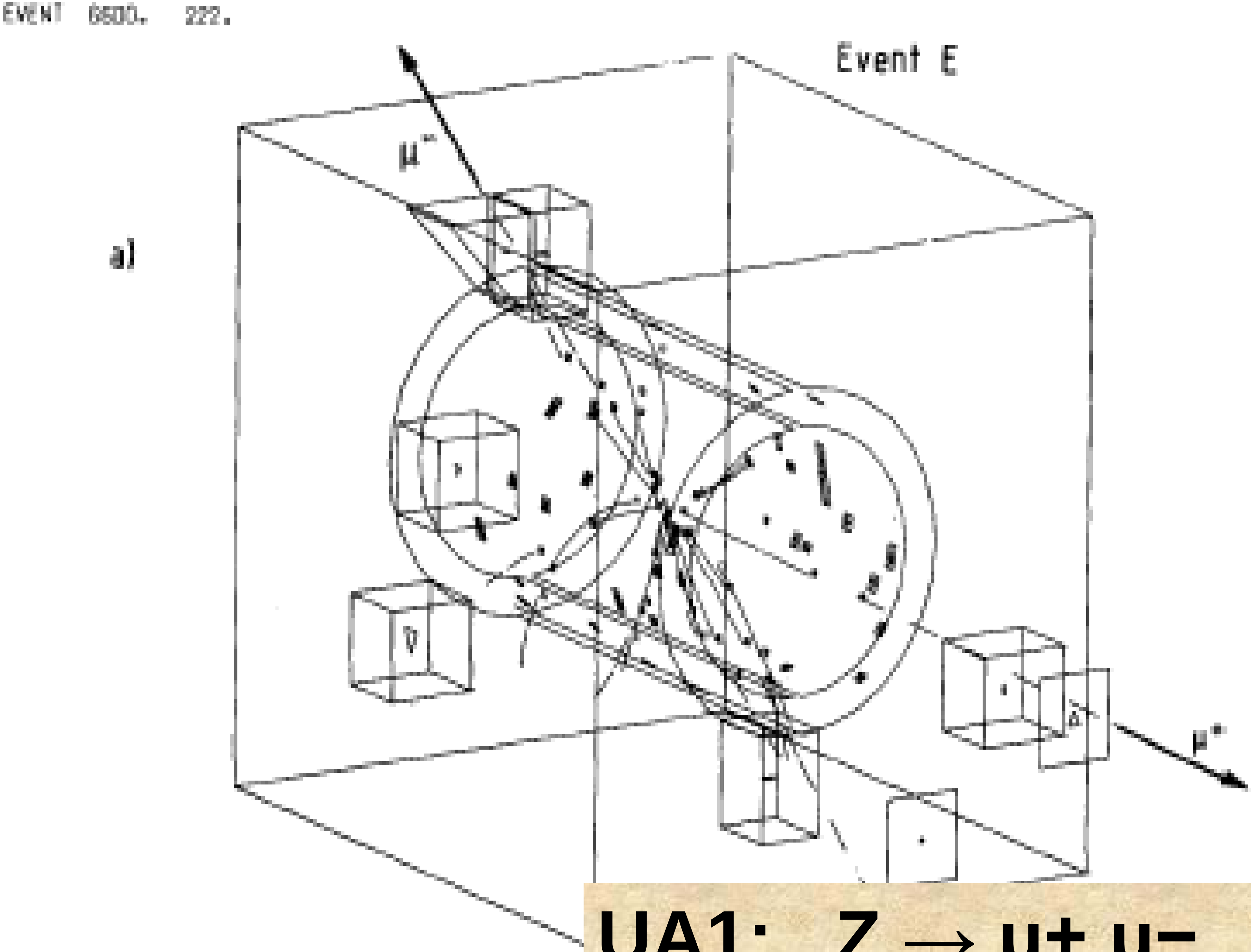
M(W)=80.4 GeV
M(Z)= 91.2 GeV



UA 1

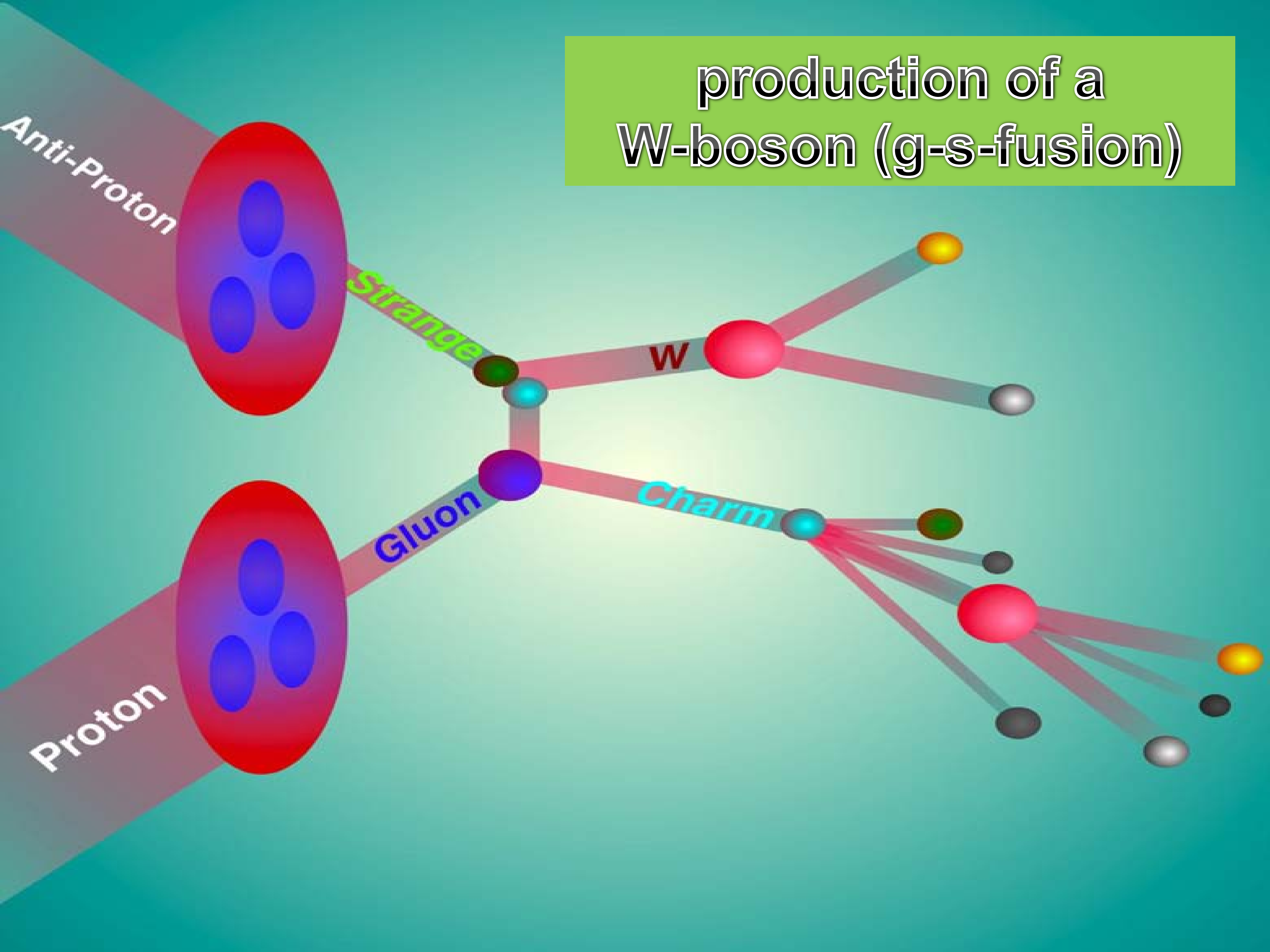
The first Z-boson, decaying into an electron and a positron

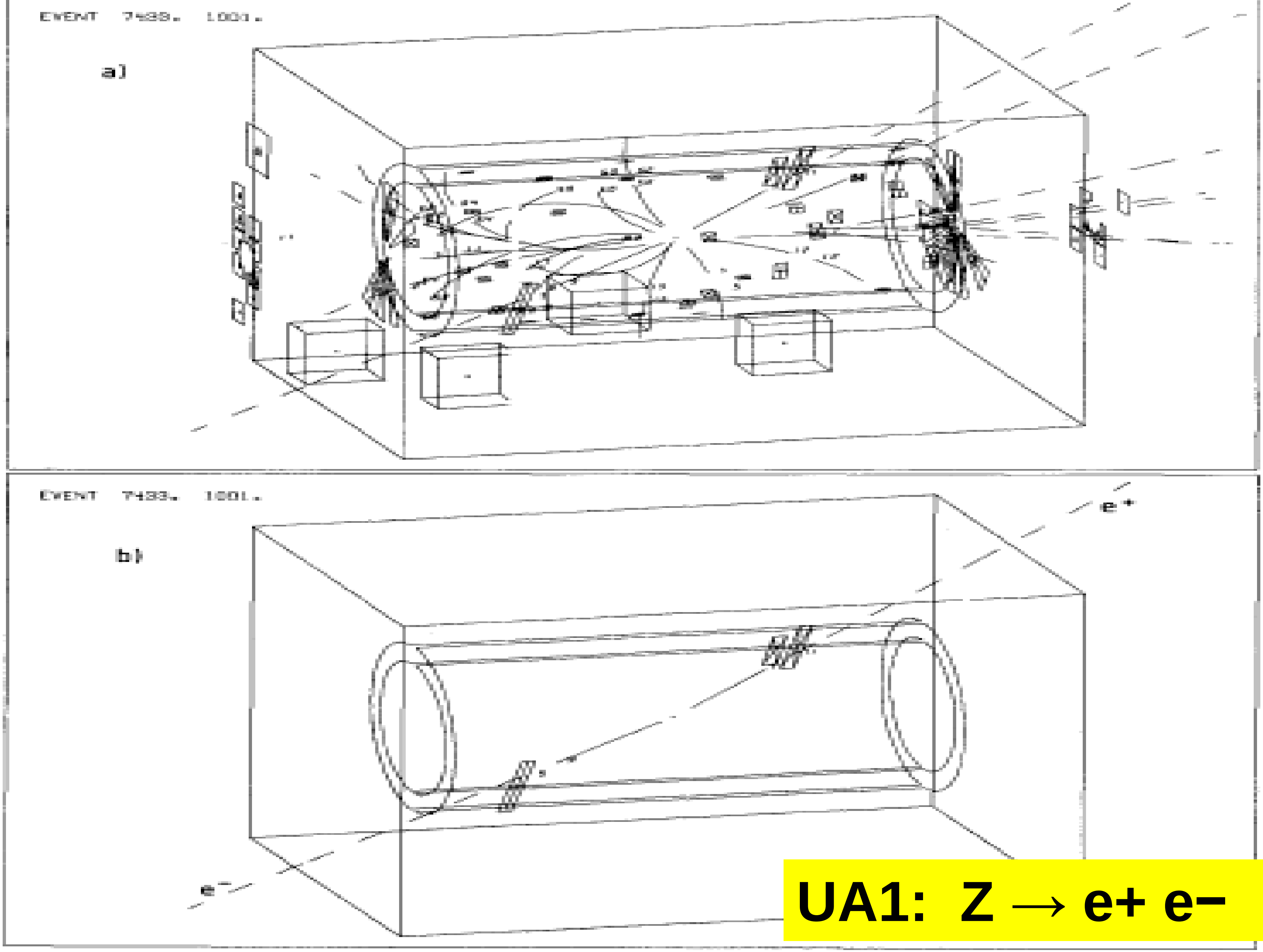

Muon from
Z decay
jet
jet
Muon from
Z decay



UA1: Z → μ+ μ−

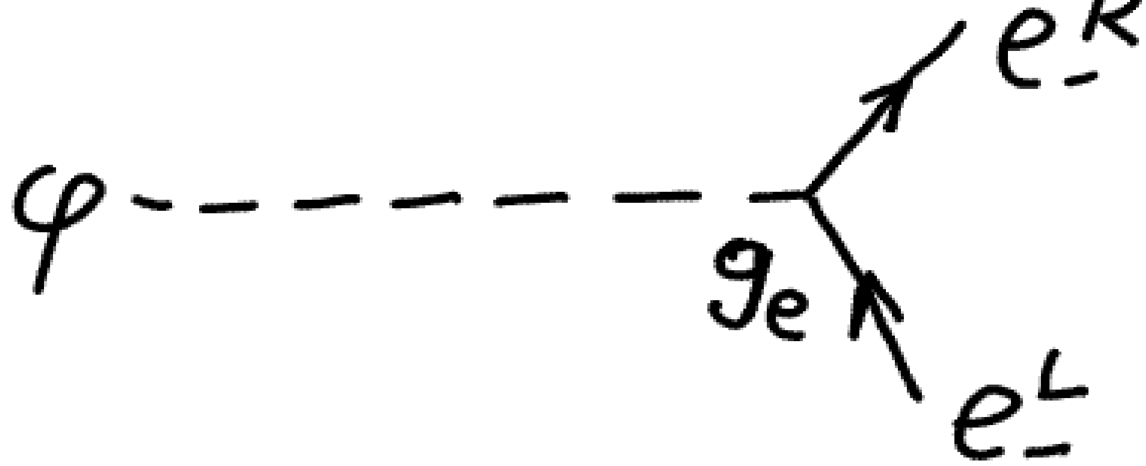
production of a W-boson (g-s-fusion)





UA1: Z → e+ e−

mass of electron:



$$m_e = g_e \cdot v \cong$$
$$\cong 2 \cdot 10^{-6} \cdot v$$
$$(v \approx 246 \text{ GeV})$$

$$M_W = \frac{37.3}{\sin\theta_W}\ \text{GeV}$$

$$M_Z = \frac{74.6}{\sin 2\theta_W}\ \text{GeV}$$

The masses of the weak bosons are predicted, once the weak angle is measured.
The electron mass cannot be predicted (the coupling constant g is unknown).

Simon van der Meer Carlo Rubbia

neutrino

massless

(only lefthanded component)

problem: mass generation

electroweak theory:

mass generation by

??? SSB ???

QCD: mass generation

by confinement

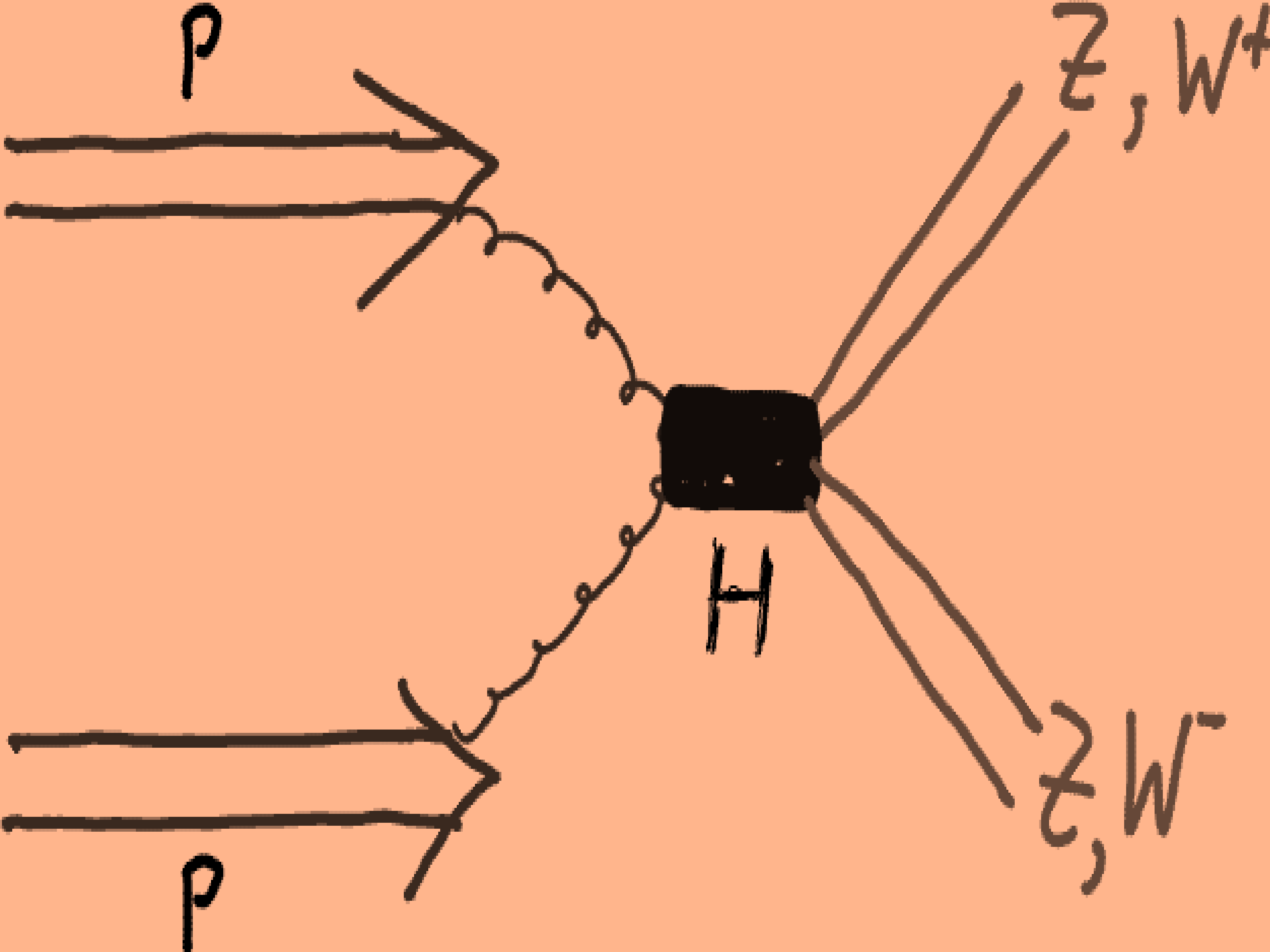
hypothetical
Higgs boson

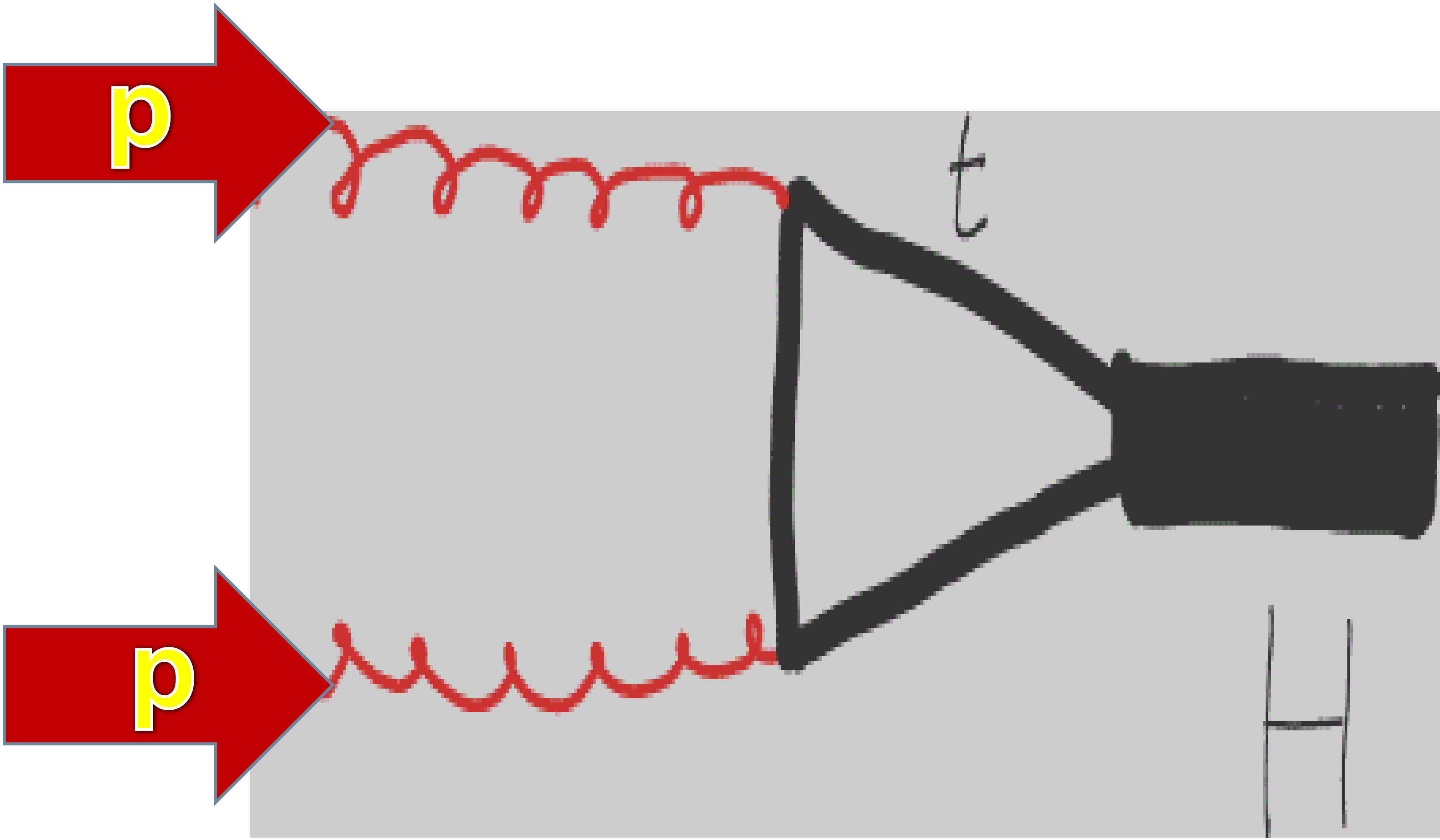
limit on mass of

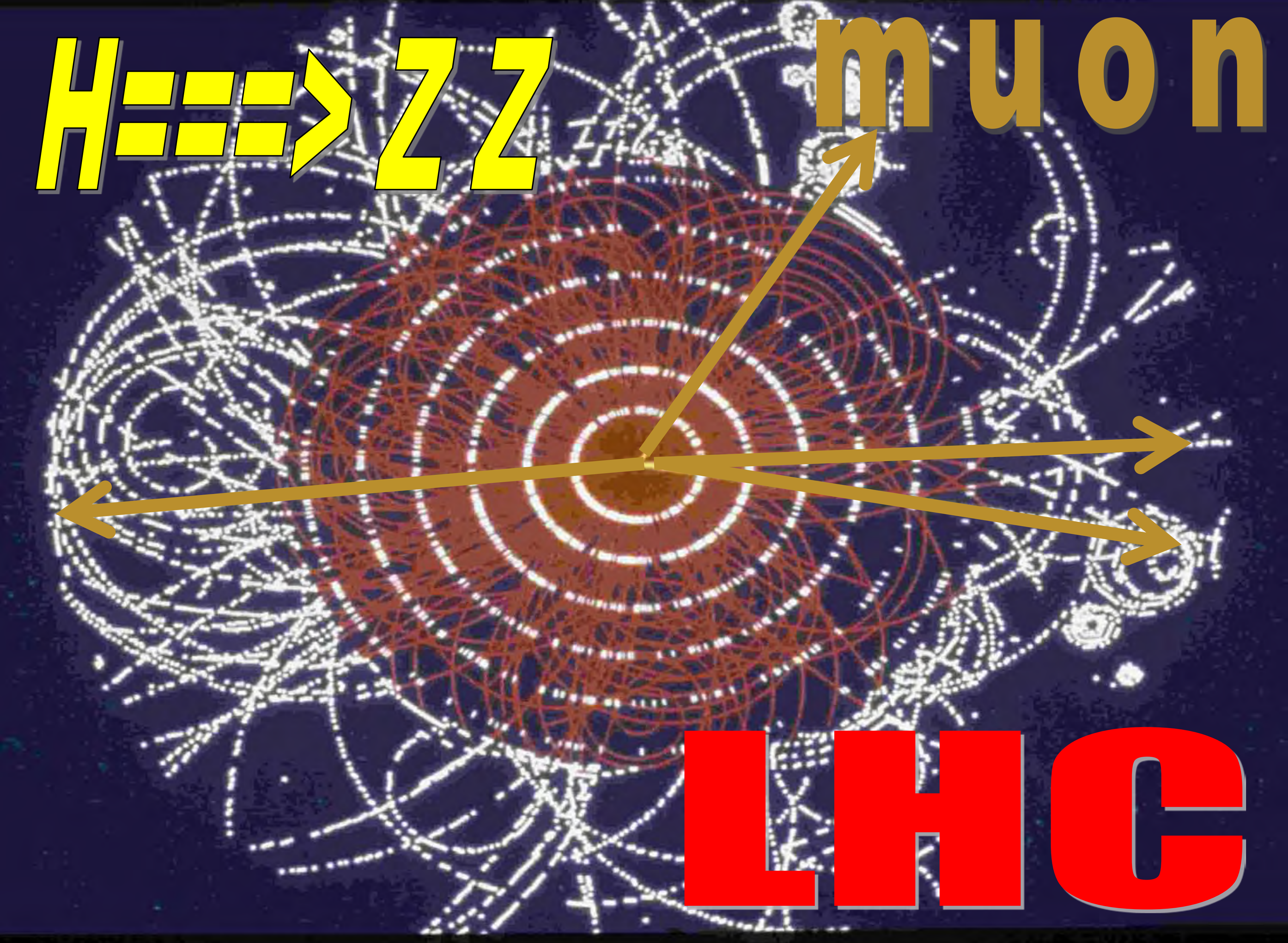
Higgs boson from LEP:

114 GeV


L3
Alice
CMS
ATLAS
LHCb
LEP - LHC


p
Z, W+
H
Z, W-
p


p
p
t
H


H===>ZZ
muon
LHC

December 2011:

ATLAS and CMS report signal at 125 GeV

decay into

Z + Z

W + W,

photon + photon